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A Distributed Multi-Robot Formation Control Method

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Abstract **- Formation control of multiple wheeled robots with nonholonomic constraints and limited acceleration has been studied in this paper. A distributed formation control method taking acceleration into account in Leader-following structure is proposed. The method uses only local sensing information and the velocity information obtained by communication. Little communication through wireless network allows robots to share their velocity information. We also developed an artificial identity mark for large scale multi-robot systems. The identity mark can not only distinguish different robots, but also measure the distance and orientation between the robots. Extensive experiments have been carried out to validate our strategy both in simulation and with real robots.**

Keywords –Multi Robot. Distributed Formation Control. Artificial Identity Mark.

I. INTRODUCTION

Multi-robot Cooperation problems have attracted increasing attention of the robot community in recent years. Formation control has been one of the important research topics in multi-robot system, which requires robots to maintain designated relative position to their peers according to a specified geometrical shape. Formation control is a good task to study motion planning of multiple robots, and it is also a prototype for many complicated task.

Various formation control algorithms have been proposed, and most of them were studied within three structures: behaviour-based structure[1], leader-following structure[2], and virtual leader structure[3]. The leader-following structure was the most popular structure for formation control and it was formulated as two popular models in [2] and [4]: $l-\varphi$ control and $l-l$ control. Many strategies and methods have been adopted to accomplish formation maintenance task in leader-following structure, e.g., Input and Output Feedback Linearization Control[2][4], Model Predicti-ve Control (MPC)[5][6], Fuzzy Logic[7]. Reinforcement Learning[8], etc.

Wheeled mobile robot with nonholonomic constraints has limited acceleration due to the limited torque of motor, but the ability of acceleration is seldom considered in current formation control works. The work in [9] presented $l-l$ control and $l-\varphi$ control model considering the acceleration ability of robot, but the method needs global knowledge of robots' position. The formation control strategy in [10] uses only local sensing information and does not share a common coordinate system, but the method is too simple to suit the situation in which the leader makes sharp turns such as to keep a circle formation.

The relative position and velocity information are very important to formation control. Different methods have been developed to study how to get this information accurately. The work in [11] used omni-directional optical flows across multiple frames to estimate the position and velocity of the leaders in the image plane of each follower. The omni-directional vision system and absolute positioning approach were used to gain these information in [2]. In [10] the Sony PTZ camera was used to gain 180 degree field of view and laser sensor was used to acquire the robots' relative distance. The robots in [10] have limited visibility, so the formation shape cannot be frontally concave. The method in [12] and [13] used time-of-flight evaluation of ultrasonic waves to perceive the distance and angle of other nearby robots, each robot determined the position of the others in relation to its own. In [14] and [15] the researchers used directional visual perception to localize robots, the method needs good uniform lighting and the cameras must rotate to keep the robot in the middle of their views.

We have studied the formation control of multiple wheeled mobile robots which have nonholonomic constraints and limited acceleration, and have been endeavouring to enable multiple robots to perform formation keeping task with distributed method. Developing the method in our earlier work[16], a $l-\varphi$ control strategy which takes the acceleration into account in leader-following structure is proposed. Different from the method in [9] which needs global coordinate knowledge, our method uses only local sensing information and the velocity obtained directly from communication. In this paper visual sensor is used to acquire the relative position information between the leader and the follower. Artificial Identity Mark base on various colours is often used to distinguish different robots. But when the robot number is very large, there are not enough colour spaces to fit the large scale multi-robot system considering the robust of detection. We developed an artificial identity mark especially for the large scale multi-robot systems. The identity mark can not only distinguish different robots, but also measure the distance and orientation between the robots. Inter-robot communication through wireless network allows them to share the velocity information. But the inter-robot communication is not necessary in every decision step; the robots only need to share their velocity information when their velocities are changed. This would reduce the communication information greatly. Our method is well-suited for distributed control and the leader robot can track any trajectory.

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The rest of this paper is organized as follows. After presenting our motion model of leader-follower for differential-driven wheeled robots in section 2, the algorithm of how to choose the optimal velocity for a formation matching function is expatiated in section 3. How to design and detect the artificial identity mark for multi-robot identification and relative position measurement is proposed in section 4. Section 5 describes the experiments with physical robots and simulated robot teams. The conclusion and our future work are given in section 6.

II. MOTION MODEL

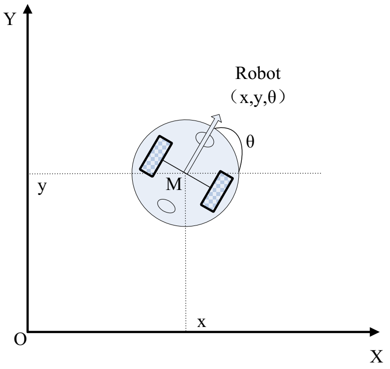


Fig. 1 Kinematical model of differential-driven wheeled robots

For a differential-driven wheeled robot R_i , (x_i, y_i, θ_i) is the position and orientation, and $u_i = (v_i, \omega_i)$ is its translational speed and angular speed. And its kinematical equation is:

$$\begin{aligned} \dot{x}_i &= v_i \cos\theta_i \\ \dot{y}_i &= v_i \sin\theta_i \\ \dot{\theta}_i &= \omega_i \end{aligned} \tag{1}$$

Assume that $x(t_1)$, $y(t_1)$, $x(t_n)$, $y(t_n)$ denote the robot position at time t_1 and t_n , the predictive equation of robot position at time t_n can be given by:

$$\begin{aligned} x(t_n) &= x(t_1) + \int_{t_1}^{t_n} v(t)\cos\theta(t)dt \\ &= x(t_1) + \int_{t_1}^{t_n} (v(t_0) + \int_{t_0}^{t} \dot{v}(\hat{t})d\hat{t})\cos(\theta(t_0) \\ &+ \int_{t_0}^{t} (\omega(t_0) + \int_{t_0}^{\hat{t}} \dot{\omega}(\tilde{t})d\tilde{t})d\hat{t})dt \\ y(t_n) &= y(t_1) + \int_{t_1}^{t_n} v(t)\sin\theta(t)dt \\ &= y(t_1) + \int_{t_1}^{t_n} (v(t_0) + \int_{t_0}^{t} \dot{v}(\hat{t})d\hat{t})\sin(\theta(t_0) \\ &+ \int_{t_0}^{t} (\omega(t_0) + \int_{t_0}^{\hat{t}} \dot{\omega}(\tilde{t})d\tilde{t})d\hat{t})dt \end{aligned} \tag{2}$$

It is assumed that the trajectory of a differential-driven wheeled robot will be a circle if the translational and angular velocities do not vary, and the curvature of circle is decided by the velocities. Under this assumption the trajectory of the robot can be approximated to sequences of segments of arc. We also assume the robot translational and angular velocities between very tiny periods do not vary. So the translational and angular velocities in $[t_i, t_{i+1}]$ are assumed as:

$$\begin{aligned} v(t) &= v_i, t \in [t_i, t_{i+1}] \\ \omega(t) &= \omega_i, t \in [t_i, t_{i+1}] \end{aligned} \tag{3}$$

Thus, the motion predictive model of robot can be simplified as:

$$\begin{aligned} x(t_n) &= x(t_1) + \sum_{i=1}^{n} \int_{t_i}^{t_{i+1}} v_i \cos(\theta(t_i) + \omega_i \cdot (\hat{t} - t_i))d\hat{t} \\ &= x(t_1) + \sum_{i=1}^{n} \frac{v_i}{\omega_i}(\sin(\theta(t_i) + \omega_i \cdot (t_{i+1} - t_i)) - \sin\theta(t_i)) \\ y(t_n) &= y(t_1) + \sum_{i=1}^{n} \int_{t_i}^{t_{i+1}} v_i \sin(\theta(t_i) + \omega_i \cdot (\hat{t} - t_i))d\hat{t} \\ &= y(t_1) + \sum_{i=1}^{n} \frac{v_i}{\omega_i}(\cos\theta(t_i) - \cos(\theta(t_i) + \omega_i \cdot (t_{i+1} - t_i))) \end{aligned} \tag{4}$$

And when $\omega_i = 0$, the equation (4) can be simplified to the following equation:

$$\begin{aligned} x(t_n) &= x(t_1) + \sum_{i=1}^{n} v_i \cos\theta(t_i) \\ y(t_n) &= y(t_1) + \sum_{i=1}^{n} v_i \sin\theta(t_i) \end{aligned} \tag{5}$$

In this paper, we use the equations (4) and (5) to estimate and predict the robot motion.

III. FORMATION CONTROL METHOD

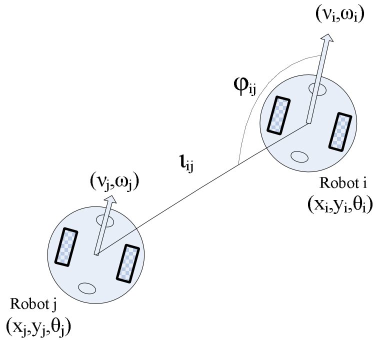


Fig. 2 Leader-Following Formation Control Model

Fig. 2 is the leader-following $l-\varphi$ formation control model, and the formation shape is designated by the relative distance l_{ij} and relative angle φ_{ij} between the two robots, *Robot i* and *Robot j* . The designated formation shape is (l_{ij}^d, φ_{ij}^d), Assume the formation error at time k is denoted by $e(k)$, and $e(k)$ is formulated by the follow equation (6). l_{ij}^k and φ_{ij}^k denote the relative distance and angle between the leader robot and the follower at time k .

$$e(k) = \begin{bmatrix} e_l^k \\ e_\varphi^k \end{bmatrix} = \begin{bmatrix} l_{ij}^d - l_{ij}^k \\ \varphi_{ij}^d - \varphi_{ij}^k \end{bmatrix} \tag{6}$$

Since the velocity of the follower in a control period is limited to a rectangular space due to its limited acceleration, we need only to search this rectangular velocity space to get an optimum velocity which can minimize the difference between the specified formation and the formation predicted. A formation matching function is defined commendably to figure out the formation difference so that the formation control problem can be changed to a problem of finding velocity sequences that can make the formation matching function optimal.

In our earlier work [16], we only predict robots' motion from time k to $k+1$. The method is to find out the optimal velocity of the follower robot that minimizes the difference between the specified formation and the formation at $k+1$ time in next control period. The strategy can achieve elegant formation control when the leader does not change its velocity frequently. When the leader changes its velocity frequently, the velocity of the follower robot will have little fluctuation. In this paper, in order to eliminate the drawback we predict the robot's motion from time k to $k+m$.

Assume $e(k+m)$ is the formation error at time $k+m$, and it can be denoted by the following equation.

$$e(k+m)=\begin{bmatrix} e_l^{k+m} \\ e_\varphi^{k+m} \end{bmatrix}=\begin{bmatrix} l_{ij}^{d}-l_{ij}^{k+m} \\ \varphi_{ij}^{d}-\varphi_{ij}^{k+m} \end{bmatrix} \quad (7)$$

The formation matching function $V(e,u,m)$ is defined as the below equation.

$$V(e,u,m)=\left[(e_l^{k+m})^2+(e_\varphi^{k+m})^2\right]+\frac{1}{m-1}\sum_{i=1}^{m-1}\left[(e_l^{k+i})^2+(e_\varphi^{k+i})^2\right] \quad (8)$$

The formation control method can be formulated as equation (9).

$$\begin{aligned}&\min_{u\in U} V(e,u,m)\\ &V(e,u,m)=\left[(e_l^{k+m})^2+(e_\varphi^{k+m})^2\right]+\frac{1}{m-1}\sum_{i=1}^{m-1}\left[(e_l^{k+i})^2+(e_\varphi^{k+i})^2\right] \quad (9)\\ &u\in U=(u_{\min},u_{\max})\end{aligned}$$

The formation control process can be described as follow steps:

(1) Given $u\in U=(u_{\min},u_{\max})$ and robot velocity $u(k)$ at current time k, Use equation (10) to compute the velocity sequence $u(k+1)$, $u(k+2)$, … $u(k+m)$.

(2) Use equation (9) and (4) to compute $V(e,u,m)$ according to the velocity sequence for each given $u\in U=(u_{\min},u_{\max})$.

(3) Choose the best velocity $u\in U=(u_{\min},u_{\max})$ to minimize the optimization value $V(e,u,m)$.

(4) Robot executes the first velocity $u(k+1)$ in the velocity sequence in next control period .

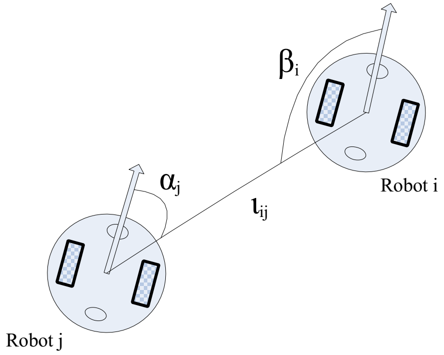
(5) At time $k+1$, back to process (1) to compute the best velocity sequence.

```
$For(i=1; i<=m; i++)$
{
    $v(k+i)=v(k)+\dot{v}\times\delta\times i;$
    $if\,(v(k+i)>=v)$
    $\{\ v(k+i)=v;\ \}$                    (10)
    $\omega(k+i)=\omega(k)+\dot{\omega}\times\delta\times i;$
    $if\,(\omega(k+i)>=v)$
    $\{\ \omega(k+i)=v;\ \}$
}
```

In step (1), the velocity sequence can be described by the following code (10). The equation (10) predicts robot's velocity sequence taking robot's acceleration into account. The δ denotes the time from time k to $k+1$.

IV. ARTIFICIAL IDENTITY MARK FOR MULTI-ROBOT

(a)Traditional identity mark



(b) Two robots' relative position and orientation

Fig. 3 Relative position and orientation in local coordinate system

The relative position and velocity information are very important to formation control. In the leader-following formation control process, the follower has to change its velocity constantly to maintain the specified position related to the leader. Most motion models used in formation control require global information, typically the position and orientation of all of the robots in a global coordinate system. But it is very difficult to get the position information for a multi-robot team especially in unknown environment. The formation control algorithm in this paper only uses the local information, and it needs the robots have the ability to identify themselves and measure their relative position. It is also very important for distributed control of multi-robot systems.

Many works[14][15] as well as our earlier work[16] used the artificial identity mark as Fig.3 (a) to identify different robot and measure relative position, because visual perception algorithm for colorful objects needs less computational burden. But using this kind of identity mark only based on one color, there are also many drawbacks, such as:

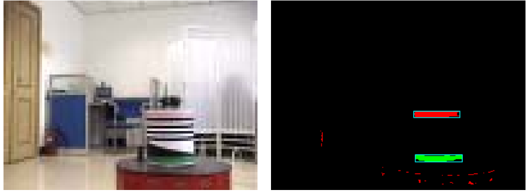
(1) The identity mark only based on one color is very imprecise-prone especially in disturbing environment.

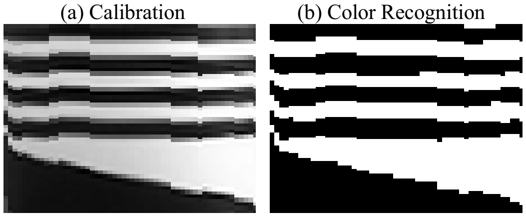
(2) Each robot must have different color. When the robot number is very large, there are not enough color spaces to fit the large robot number considering robust detection.

(3) For identity mark based on color, it is necessary to calibrate aforehand. When the robot number is very large, it will take a lot of time to calibrate.

(4) For multi-robot system, the relative orientation of robots is also very important. When the multi-robot system doesn't have the global localization capability, robot must use their sensor information to get relative orientation. For instance, two robots don't have their position information in global

coordinates system. Assume *Robot i* can get the information l_{ij} and β_{ij}, and *Robot j* can get the information l_{ij} and α_{ij}. If the two robots want to compute their relative orientation, they have to exchange their sensor information in real time. The communication delay would effect the precise of the relative orientation, and that would present rigorous performance for multi-robot communication system.


(a) Calibration (b) Color Recognition


(c) Extracting Middle Region (d) Histogram Equalizing

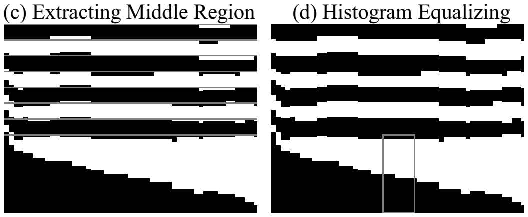

(e) Compute Barcode (f) Compute Orientation

Fig. 4 Artificial Identity Mark Recognition Result

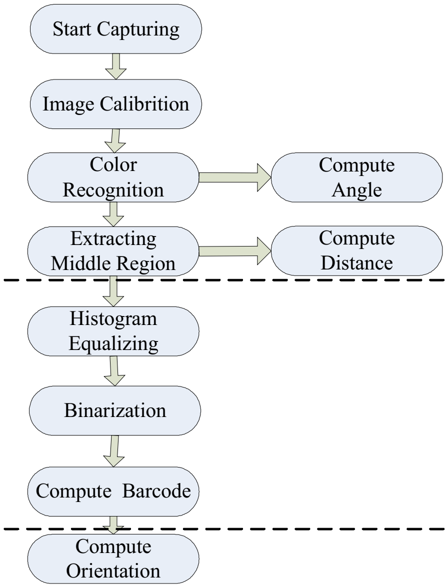


Fig. 5 Artificial Identity Mark Recognition Process

A novel artificial identity mark for multi-robot is proposed in this paper to eliminate the drawbacks mentioned above. The profile of the identity mark is showed in the Fig.4 (a). The identity mark is composed of three components: color zone, barcode zone and triangle zone. Two different color zones are located respectively at the top and bottom of the identity mark; they are designed for mark detection. The barcode is designed to distinguish different robot. The triangle zone is designed to measure the robot's orientation.

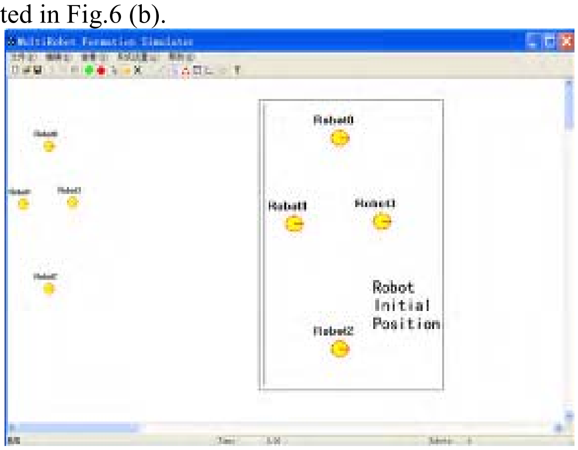
The process to identify the mark and compute relative position and orientation is showed as Fig. 5, and the recognition result is showed as Fig. 4. The measurement error using the mark to measure relative position and orientation will be presented in section 5.

V. EXPERIMENTS

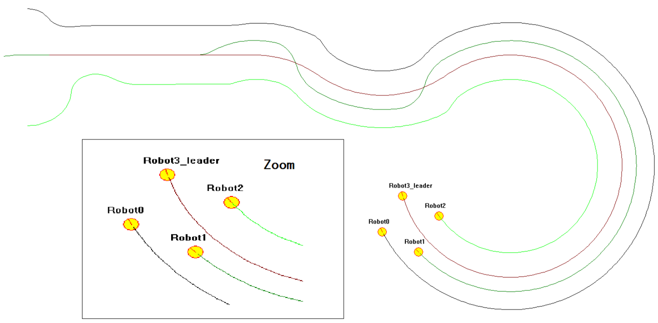
A. *simulation Results*

We demonstrated our algorithm with numerous simulations and physical experiments. The simulation experiments are running on our multi-robot simulation platform developed by visual C++. In simulation experiments, Formation establishing and formation maintaining processes are done synchronously. The designated trajectory of leader is composed of line, arc, and circle, and the followers can modify their velocity to keep designed shape with the leader robot.

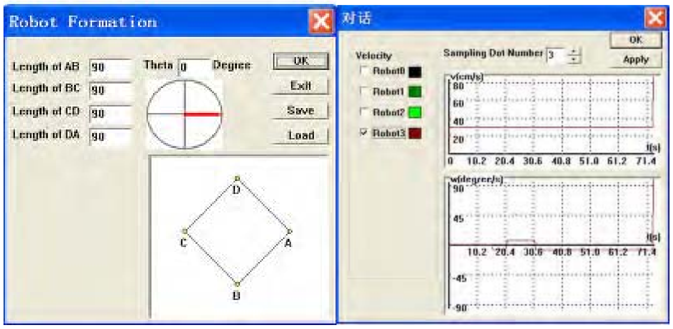
In Fig.6, four robots are designated to keep a diamond formation. The initial position of four robots is set up stochastically as Fig.6 (a), and the designated geometry shape and the leader robot's velocity information are showed in Fig.6 (c) and (d). We can find the three follower robots' velocity information in Fig.6 (e). Four robots' trajectories are painted in Fig.6 (b).



(a) Robot Initial Position

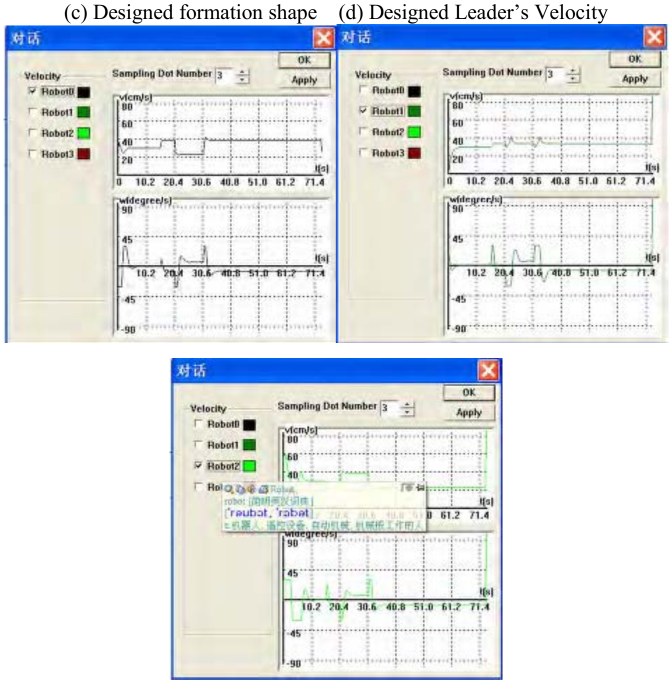


(b) Robot Motion Trajectory



Length of AB 90
Length of BC 90
Length of CD 90
Length of DA 90
Theta 0 Degree
Sampling Dot Number 3

(c) Designed formation shape (d) Designed Leader's Velocity



Sampling Dot Number 3

(e) Three Followers' Velocity Information

Fig.6 Simulation Display (Four robots keep diamond shape)

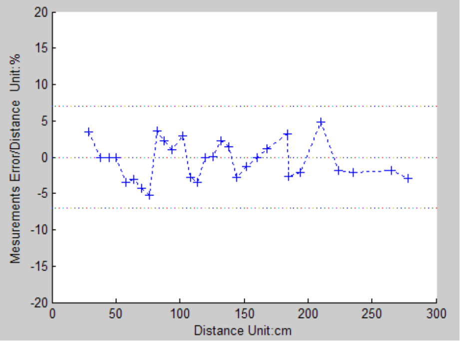
B. Experiments with Real Robots

The proposed algorithm is also validated using our mobile robot platform-AIM Robot (see Fig.3). AIM Robot is a differential-driven wheeled robot equipped with 4 CCD cameras, Wireless network Adapter, 16 ultrasonic sensor, and 16 infrared sensors. The diameter the AIM Robot is about 50 centimeters.

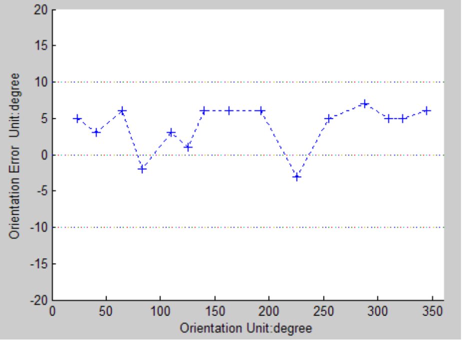
In order to use visual information to get the relative position and angle of the robots, cylinders attached with Artificial Identity Mark are placed on the top of robots. In the experiments four cameras are used to gain 360 degree view field. The visual information processing for 4 cameras can be done in 40 milliseconds. Inter-robot communication using wireless network allows the robots sharing their relative velocity information.

The measurement errors using the artificial identity mark for robots to measure relative distance and orientation are showed in Fig.7. When robots' relative distance is within 300 centimeters, the measurement error is below 5 percent (see Fig.7 (a)). And measurement error for orientation is with 6 degree (see Fig.7 (b)). The data is measured under the condition that two robots' relative position angle is about 25 degree.

In experiments with real robots, the follower acquired the relative position of the leader with its vision system and then got the leader's velocity information through wireless network. The follower chose its optimal velocity to reach the formation with the information obtained by its sensor and the information received from the leader. The formation shape and leader robot's velocity was set as Table 1.



(a) Error for distance



(b) Error for Orientation

Fig. 7 Measurement Error for Identity Mark

Table 1 parameters setting of experiment with real robots

	Exp. 1	Exp. 2	Exp. 3-1	Exp. 3-2
Designed distance- l	80cm	80cm	80cm	80cm
Designed angle- φ	150°	150°	150°	220°
Leader's translational speed	30cm/s	30cm/s	30cm/s	30cm/s
Leader's angular speed	0°	10°	0°	0°

In experiment 1, the leader robot followed a line trajectory. The designated l was 80 centimetres, and the designated φ was 150 degree. The experiment snapshots are showed in Fig.8. In experiment 2, the leader robot followed a circle trajectory, and the formation shape is same with experiment 1. Three robots kept a triangle shape in experiment 3. The experiment snapshots are showed in Fig.9 and Fig.10.

VI. DISCUSSION AND CONCLUSION

This paper focuses on the formation control of multiple differential-driven wheeled mobile robots. A new $l-\varphi$ control strategy in leader-following structure is presented. The new control strategy is derived directly from the dynamic of robot. It takes the acceleration ability of robot into account and uses only local sensing data and small data communication to achieve elegant formation control. This method is well-suited for distributed control. It has been shown by extensive experiments that the proposed method is quite effective for formation establishing and is stable for maintaining the formation. Robots can achieve specified formation fleetly within their abilities.

Future work will involve testing the convergence of our method in any condition. We will also concentrate on the formation switching and obstacle avoiding problem.

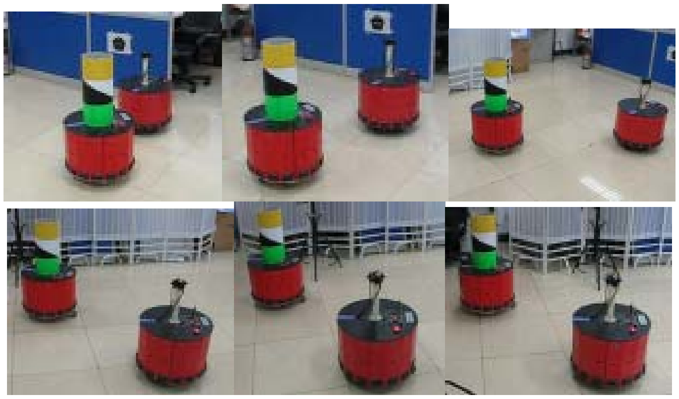


Fig. 8 Experiment 1 snapshots

Fig. 9 Experiment 2 snapshots

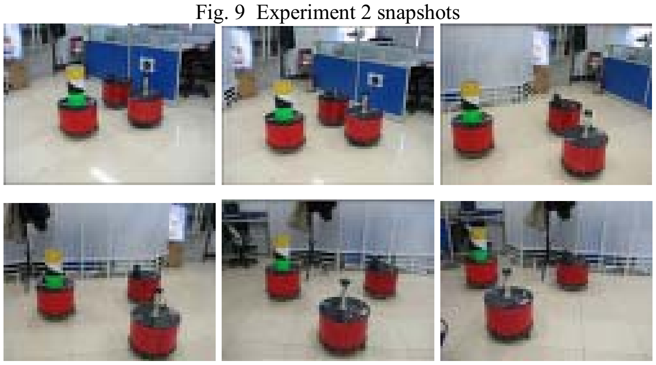


Fig. 10 Experiment 2 snapshots

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